



Numerical Study of Water and Energy Field in Eastern Siberia Focusing on Air-Land Interaction

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論文目次

Abstract

List of Figures

List of Tables

Acknowledgments

1. Introduction

1.1 Background

1.2 Purposes of This Study

2. Model Description

2.1 Land Surface Process

2.1.1 Soil Temperature

2.1.2 Evaporative Efficiency of Land Surface

2.1.3 Stomatal Resistance

2.2 Turbulent Process

2.2.1 Turbulent Equations with Reynolds Average

2.2.2 Closure Model

2.3 Precipitation Process

3. Influence of Land Cover Change on Regional Water and Energy Field

3.1 Introduction

3.2 Factors Deciding Water and Energy Field

3.2.1 Experiment Design

3.2.2 Result

3.2.3 Discussion

3.3 Water and Energy Field Change with Land Cover Change

3.3.1 Introduction

3.3.2 Method

3.3.3 Result

3.3.4 Discussion

3.4 Summary

4. Roles of Eastern Siberia Mountain Ranges to Water Field

4.1 Introduction

4.2 Forest Survey and Water Field in Eastern Siberia

4.2.1 Forest Survey

4.2.2 Distribution of Precipitation

4.2.3 Water Vapor Flux

4.3 Experiment Design

4.4 Results and Discussion

4.4.1 Control Run

4.4.2 Verkhoyansk Mountain Range

4.4.3 Dzhugdzhur Mountain Range

4.4.4 Stanovoy Mountain Range

4.5 Mountain Range Impact on Precipitation in Regional Scale

4.6 Summary

5. Conclusions

論 文 内 容 要 旨

According to Intergovernmental Panel on Climate Change 4th Activity Report (IPCC AR4), surface temperature in Eastern Siberia will increase around 2 °C in 2020-2029 and 6 °C in 2090-2099. These surface temperature rising are obviously larger compared with other regions. Not only predicted future environment change but also present environmental changing is already reported by researchers on Eastern Siberia, such as water surface expanding or deforestation with increasing of forest fire frequency. Alas is the last stage of thermokarst depression, which is made by repetition of freezing and thawing ground soil. In general, Alas consists of grassland and water surface in center and it takes 10,000 years for formation, however, water

surface expanding, which is recently reported, is quite rapider than its formation. On the other hand, from meteorological standing viewpoints, land surface state can be described using parameters such as surface albedo, evaporative efficiency. Thus when land surface change, these parameters vary and water/energy balance also varies at the same time. Moreover, according to previous study on water recycling ratio, more than 60 % of precipitation source is supplied by evapotranspiration from land surface and this trend becomes stronger in Eastern Siberia than Western Siberia. Thus it is necessary to investigate water and energy field change with each land surface parameter change based on parameter impact in Eastern Siberia. Another precipitation source, which is 40 % of precipitation, is maintained by water vapor advected from ocean. In general, water vapor flux and precipitation are affected by topography. Eastern Siberia is surrounding by three mountain ranges: Verkhoyansk mountain range in north part, Dzhugdzhur mountain range in southeast part and Stanovoy mountain range in south part. In Eastern Siberia, the relationship between precipitation and mountain ranges is still not clear because atmospheric study using three-dimensional atmospheric model have not been conducted until now.

This thesis has two objectives:

- 1) to make clear water and energy field change with land surface change
- 2) to understand roles of three Eastern Siberia mountain ranges on water field.

Numerical experiment is effective method to satisfy these objectives. Non-Hydrostatic Model that is developed by Japan Meteorological Agency and Meteorological Research Institute (JMA-NHM) is used in this study. The outline of the model focused on land surface process and precipitation process was described in Chapter 2.

In Chapter 3, first topic is water and energy field response for each change of five land surface parameters: surface albedo, evaporative efficiency, roughness length, heat capacity and thermal conductivity. Considering land surface change is mainly occurred in low elevation area, parameter change was conducted for less than 250 m above sea level (a.s.l.) area. Parameter impact is defined as area-averaged latent heat flux variation or precipitation variation for parameter variation, surface albedo and evaporative efficiency had larger parameter impact among five land surface parameters. On the other hand, roughness length, heat capacity and thermal conductivity had lower parameter impact on water and energy field in Eastern Siberia.

Second topic of Chapter 3 is to make clear how water and energy field change with land surface change in Eastern Siberia based on parameter impact. Considering Alas area distributes almost 20 % of lowland Central Yakutia, water and energy field difference between grassland 20 % run and water surface 20 % run was analyzed. Here, land surface distribution of grassland, water surface and original is denoted as (G, W, O). For example, distribution of grassland 20 %, water surface 0 % and original 80 % can be written as (G, W, O) = (0.2, 0.0, 0.8). There was linear increase of latent heat flux with water surface expanding from (G, W, O) = (0.2, 0.0, 0.8) to (0.0, 0.2, 0.8) and degree of latent heat flux increase was 1.2 W m^{-2} (2.4 %). To understand what parameter played important role for this result, each land surface parameter effect was estimated from parameter impact and parameter change in Lena basin scale. According to parameter impact result, surface albedo and evaporative efficiency are impactful parameter on water and energy field. However, surface albedo was not effective parameter for water surface expanding, because degree of actual surface albedo change (-0.006) was not so large compared with other surface parameters. Surface albedo has higher parameter impact, but its actual parameter change was lower value. Thus it did not become impactful parameter. Similar

discussion can be done for thermal conductivity, actual parameter change of thermal conductivity was secondary larger value among five land surface parameters ($+0.115 \text{ W m}^{-1} \text{ K}^{-1}$). However, parameter impact of thermal conductivity was secondary lower value. Lower parameter impact and higher actual parameter change was found for thermal conductivity, therefore, it also did not play important role with water surface expanding. On the other hand, evaporative efficiency, which was larger parameter impact, has one-order larger actual parameter change ($+0.049$) than surface albedo. Thus water and energy field change with water surface expanding was controlled by evaporative efficiency.

Using parameter impact and virtual land surface data, we can estimate water and energy field change in regional scale in order to understand not only water surface expanding but also deforestation. Latent heat flux increased by 0.1 W m^{-2} from $(G, W, O) = (0.2, 0.0, 0.8)$ to $(1.0, 0.0, 0.0)$, however, it was 0.5 W m^{-2} from $(G, W, O) = (0.2, 0.0, 0.8)$ to $(0.0, 0.2, 0.8)$. Although later one was just only 20 % land surface change, the latent heat change was five times larger than all under 250 m a.s.l. area was covered by grassland. Thus land surface change to grassland does not have strong impact to water and energy field, but land cover change that contains water surface enhances latent heat flux strongly.

In Chapter 4, focusing point is moved to relationship between precipitation and three mountain ranges in Eastern Siberia: Verkhoyansk mountain range, Dzhugdzhur mountain range and Stanovoy mountain range. Starting point of this chapter is forest survey in Elgeei site (relatively south in Lena basin) and its comparison with Spasskaya Pad site (350 km northwest from Elgeei). Averaged tree height and maximum tree height took larger value in Elgeei site, thus it was thought that southern Siberia was favorable environment for tree growth, such as much precipitation. According to routine station data, much precipitation in southern Siberia was found not only relation between Elgeei and Spasskaya Pad but also overall Eastern Siberia.

Precipitation and water vapor flux have strong relationship each other, thus water vapor flux budget was investigated for Eastern Siberia. Taking budget box encircled with line of $59^\circ - 71^\circ \text{ N}$ and $116^\circ - 138^\circ \text{ E}$, mainstream of vertical integrated water vapor flux was inflow through west-side and outflow through east-side, net flux through south and north-sides were one-order smaller than east and west-sides. This trend became different when net flux separated into incoming and outgoing component; incoming and outgoing water vapor flux through south-side was large as much as water vapor flux through west-side. There is Stanovoy mountain range in just south of the budget box, therefore water vapor flux and precipitation may be affected by the mountain range. Not only Stanovoy mountain range but also other two mountain ranges, Verkhoyansk mountain range and Dzhugdzhur mountain range, are located in Eastern Siberia. Therefore sensitivity experiment of mountain range disappearance was conducted to make clear roles of mountain ranges in Eastern Siberia.

Averaging from 110° to 140° E , it was found that Verkhoyansk mountain range had little effect on precipitation. Precipitation decrease was 0.2 mm day^{-1} with 200 - 400 m topography excavation, it was around half of other two mountain ranges. This small precipitation change was caused by lower specific humidity, which was 0.0003 to 0.0004 kg kg^{-1} over Verkhoyansk mountain range, however, it was 0.004 to 0.006 kg kg^{-1} over Stanovoy mountain range and Dzhugdzhur mountain range. Relatively low precipitation source was exist over Verkhoyansk mountain range, thus its impact was smaller than other two mountain ranges. However, when we focused on 133° E cross-section, relatively higher specific humidity could not keep in Lena basin without Verkhoyansk mountain range. This moistening was not found in 62° N cross-section, Verkhoyansk mountain range moistens Lena basin for east-west direction.

Dzhugdzhur mountain range had larger precipitation decrease than Verkhoyansk mountain range with its disappearance. The maximum decrease area was found in southern edge of Dzhugdzhur mountain range area. Specific humidity took higher value in southern area, thus its impact on precipitation was larger than Verkhoyansk mountain range. Moreover, precipitation decreased area was good agreement with elevation decrease area, therefore precipitation over Dzhugdzhur mountain range was maintained by orographical effect.

Stanovoy mountain range had similar precipitation decrease with its disappearance, which was 0.4 mm day^{-1} . Both Eastern and western edges of precipitation decrease area had corresponded to elevation decrease area, however, precipitation of saddle part did not decrease even if the saddle part had been removed. In control run, there were two precipitation patterns associated with Stanovoy mountain range: low pressure pattern and frontal precipitation pattern. Low pressure precipitation pattern passed over the saddle part in control run, however, it did not disappear in no Stanovoy mountain range run. Thus eastern and western part of Stanovoy mountain range is orographical effect precipitation area and the saddle part is non-orographical precipitation area such as low pressure pattern.

This thesis presented water and energy field in Eastern Siberia based on air-land interaction using three-dimensional atmospheric model (JMA-NHM). Many studies have been conducted in Eastern Siberia from 1990s, not only observational studies but also modeling studies was developed with corporation each other. However, as problems of observational studies, limited observational sites can be pointed out; for modeling studies, little treatment of interaction between land surface and the atmosphere. Evapotranspiration from land surface becomes source for precipitation, therefore water movement between land surface and the atmosphere should be treated for modeling study. Because this thesis covers Eastern Siberia in regional scale and treats that interaction, we believe our new findings will accelerate Eastern Siberia studies not only modeling studies but also observational studies.

At last, I would like to point out three issues for more progress of this study. First point is collaboration with water surface expanding model on atmospheric model. In Chapter 3, latent heat flux change with land surface change was shown as possibility, but land surface change should be expressed explicitly for future prediction. Second point is also concerned to Chapter 3, improvement of initial and boundary condition is needed for calculation. Water surface expanding may occur in future, thus not only modification of land surface model but also improvement of atmospheric condition such as initial and boundary condition that is calculated by Global Circulation Model with global warming scenario is needed for future prediction. Third point is to introduce carbon cycle to numerical model. Water and energy field were focused in this study, but carbon cycle was not treated. To capture water and energy cycle, to introduce of carbon cycle should help more precise understanding. For example, photosynthesis, this occurs with transpiration, affects not only water and energy cycle but also carbon cycle. Thus considering and introducing carbon cycle to numerical model such as JMA-NHM should help us for understanding water, energy and carbon cycle in Eastern Siberia.

論文審査の結果の要旨

東シベリアは温暖化の影響を強く受ける地域として注目されている。しかし、これまでの同地域の研究は、いわゆるプロットスケールの観測と1次元モデルを基礎とするものが中心で、大気モデルを使った水・熱循環や陸面・大気相互作用に関する研究はほとんど行われてこなかった。吉田龍平提出の論文は、東シベリアにおける水・熱循環に関する大気の数値モデルを用いた研究である。

まず、水平格子5 kmの気象庁非静力モデルNHMを用いて、この地域の地表面蒸発散（潜熱）を規定する要素は何かを調べた。一般に、数値モデルにおいては、地表面の性質は地表面パラメータと呼ばれるもので記述される。本論文ではアルベド（日射の反射率）、蒸発効率、粗度、熱伝導率、熱容量の5つの地表面パラメータに対する敏感度を算出した。その結果、蒸発効率とアルベドが蒸発散を規定することを示した。続いて、近年報告されている水体面積の増加や森林減少のような地表面状態の変化が、水環境に及ぼす影響を地表面パラメータに対する敏感度を用いて調べた。結果として、森林面積が変わらず、草地が水体化しても蒸発散・降水量への影響は少ないことを示した。一方、森林面積が減少して水体が増えると、蒸発散・降水量に顕著な影響が生じることを初めて明らかにした。

次に、東シベリアを囲む山脈が水循環に与える影響について調べた。東シベリアへの夏季の水蒸気供給は西からの寄与が大きい、南側でも正味は小さいものの水蒸気の出入りは大きいことを再解析データにより明らかにした。水蒸気の流入と蒸発散、降水についてレナ川流域を囲む北・東・南の山脈の果たす役割について、1990年6～8月を対象として、水平格子30 kmのNHMによって調べた。北のベルホヤンスク山脈と東のジュグジュル山脈は地形効果による降水が支配的であること、南のスタノボイ山脈は東西部分では降水が多くこれは地形効果で説明できるが、中央の鞍部は低気圧による非地形的な降水が寄与していることを見出した。

本論文は東シベリアの水・熱循環の理解を大きく前進させ、近未来予測の信頼度を格段に向上させるものであり、本人が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって、吉田龍平提出の博士論文は、博士（理学）の学位論文として合格と認める。